

EXAMINATION OF MONTEITH'S PARAMETERIZATION OF CANOPY RESISTANCE

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INTRODUCTION

For more than twenty years, the most common approach to parameterize the effect of environmental factors on stomatal behaviour has been the so-called Jarvis type models (Jarvis, 1976), in which stomatal resistance is expressed as a minimum resistance multiplied by a series of independent stress functions combined in a multiplicative way (each function representing the influence of one factor). Recently, the response of stomata to humidity has been reinterpreted in a different way: It seems that the correlation between stomatal resistance and atmospheric humidity is purely empirical and that the mechanism underneath is based on the water-loss rate of the leaf (Mott and Parkhurst, 1991). Stomata appear to respond to the rate of transpiration rather to air humidity per se. Monteith (1995a,b) showed that the leaf stomatal conductance can be interpreted as a linear decreasing function of transpiration with two empirical parameters: a maximum conductance and a maximum rate of transpiration. He suggested also that this relationship between stomatal conductance and transpiration rate could be up-scaled from leaf to canopy, in the same way as the Jarvis model. The aim of this paper is to assess and discuss this new formulation of stomatal behaviour proposed by Monteith and to interpret the parameters at canopy scale.

MONTEITH'S FORMULATION

The Penman-Monteith single-source model (Monteith, 1981) gives the flux of evaporation from a fully-covering canopy in the form of the following equation

$$IE = \frac{eA + rID / r_a}{e + 1 + r_s / r_a} \quad (1)$$

where $A = R_n - G$ is the available energy (with R_n the net radiation and G the soil heat flux), $D = q^*(q) - q$ is the potential saturation deficit of the air (with q the air temperature and q the specific humidity of the air), e is the dimensionless slope of the saturation specific humidity q^* and varies with air temperature, r_a is the bulk aerodynamic

resistance to heat and water vapour transfer through the surface layer, r_s is the bulk surface resistance to water vapour transfer, r is the air density and I is the latent heat of vaporisation. Defining potential evaporation from a given vegetation canopy (denoted by E_p) as the evaporation from this canopy when all the exchange surfaces are saturated, i.e., when $r_s = 0$ in Eq.(1), evaporation can also be expressed as a function of E_p as

$$E = kE_p \quad \text{with} \quad k = 1 / \left(1 + \frac{1}{e} \frac{r_s}{r_a} \right) \quad (2)$$

According to Monteith (1995a,b) the canopy surface resistance reads as

$$r_s / r_{sn} = E_x / (E_x - E) \quad (3)$$

In this analysis soil evaporation is assumed to be negligible, which means that transpiration rate in Eq.(3) is strictly the same as canopy evaporation in Eq.(1) or (2). Consequently, combining Eq.(2), expressing the thermodynamic dependence of E on r_s , with Eq.(3), expressing the physiological dependence of E on r_s , leads to a quadratic expression for r_s , whose appropriate root is

$$r_s = \left[-\Lambda + \sqrt{\Lambda^2 + 4(1+e)r_a r_{sn}} \right] / 2 \quad (4)$$

with $\Lambda = (1+e)r_a(1 - E_p / E_x) - r_{sn}$

When the quadratic equation obtained by combining Eq.(2) with Eq.(3) is solved in E instead of r_s , the appropriate root gives (Monteith, 1995b)

$$E = \left[E_p + a_n E_x - \sqrt{(E_p + a_n E_x)^2 - 4E_x E_p} \right] / 2 \quad (5)$$

with $a_n = 1 + \frac{1}{e+1} \frac{r_{sn}}{r_a}$

The limit rate of transpiration E_x is a notional maximum rate of water supply, the precise significance of which is not known. However, a simple physical interpretation can be inferred

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from Eq.(5). When atmospheric demand becomes very large, i.e., when E_p tends to infinity (all other parameters being kept constant), it can be shown from Eq.(5) that evaporation tends to E_x . So, E_x can be interpreted as the limit value of actual evaporation when the atmospheric demand tends to infinity. In other words, it is a notional maximum amount of water available in the soil for extraction by the canopy per unit time. Little is known also on the significance and possible values of r_{sn} .

THE JARVIS TYPE REPRESENTATION

The Jarvis type models (Jarvis, 1976; Stewart, 1988) describe the response of stomata to environmental factors (at leaf scale as well as at canopy scale) in the form of a minimal resistance multiplied by the product of independent stress functions interacting without synergy

$$r_s = r_{smin} F_1(S) F_2(T) F_3(D) F_4(\Psi_l) \quad (6)$$

Here, r_{smin} is the minimum stomatal resistance observed in optimal conditions, i.e., if none of the controlling variables is limiting (it is taken to be equal to 40 s m^{-1} in our analysis). S is the incoming solar radiation, T is the air temperature, D is the water vapour saturation deficit, Ψ_l is the leaf water potential, which at the scale of a stand of vegetation is often replaced by the bulk soil water potential or the soil water content averaged over the root zone. Each function (F) varies from unity to infinity.

The influence of solar radiation can be expressed in terms of a hyperbolic function of the form (Stewart, 1988)

$$F_1(S) = (c + S) / (dS) \quad (7)$$

where d is obtained from $d=1+c/1000$. When S is expressed in W m^{-2} , Stewart and Gay (1989) derived a mean value of about 400 for c in the case of the Konza Prairie in Kansas (FIFE data). The response of stomata to temperature is not essential and will be skipped in this analysis. For the dependence on saturation deficit $F_3(D)$, the common form generally adopted is a linear decrease of stomatal conductance with D (Jarvis, 1976; Stewart, 1988) leading to

$$F_3(D) = (1 - aD)^{-1} \quad \text{with} \quad 0 < D < 1/a \quad (8)$$

For the Konza Prairie in Kansas (FIFE data), Stewart and Gay (1989) give a mean value of about 24 to the empirical coefficient a , with D expressed in kg kg^{-1} . However, Lynn and Carlson (1990, p.17) question the real effect of air humidity on stomatal resistance. They think the

role played by the saturation deficit is indirect. An increase of D damps the leaf water potential which, in turn, is responsible for an increase of stomatal resistance. As to the dependence of stomatal resistance on leaf water potential it can be expressed in different ways (Jarvis, 1976; Choudhury and Idso, 1985). In their IAGL (Institut d'Astronomie et de Géophysique Georges Lemaître) land surface model, de Ridder and Schayes (1997) employ an hyperbolic dependence of the form

$$F_4(\Psi_l) = (1 - \Psi_l / \Psi_{cc})^{-1} \quad (9)$$

where Ψ_{cc} represents the value of leaf water potential at which a complete stomatal closure occurs ($\Psi_{cc} \approx -25$ bars).

MATCHING THE TWO FORMULATIONS

In this section we show how the Jarvis model can be transformed and put in the same form as the Monteith model.

The bulk leaf water potential Ψ_l is related to the bulk soil water potential Ψ_s by means of the Ohm's law type equation originally proposed by van den Honert (1948)

$$\Psi_l = \Psi_s - r_{sp} I E \quad (10)$$

where r_{sp} is the total soil-plant resistance and E is the water flux through the soil-plant system, assumed here to be equal to the total evaporation rate. The significance and value of r_{sp} have been extensively discussed by Lynn and Carlson (1990). r_{sp} is the sum of a soil-root interface resistance (r_{sr}) and of a root-stem resistance (r_{rs}): $r_{sp} = r_{sr} + r_{rs}$. The plant component of r_{sp} (r_{rs}) remains relatively constant over a large range of leaf water potential: a typical value is 0.047 (Ψ being expressed in bar and $I E$ in W m^{-2}). The soil component of r_{sp} (r_{sr}) expresses the resistance of the flow of liquid water from the soil to the roots. The formulation proposed by Choudhury and Idso (1985) is

$$r_{sr} = 0.0013 k_1 / (Z_{ef} K_s) \quad (11)$$

where 0.0013 (m^2) is the ratio of a parameter relating root distance and geometry to the reciprocal of the effective rooting depth; k_1 is a conversion factor equal to $0.4 \cdot 10^{-10}$ when r_{sr} is expressed in bar (W m^{-2})⁻¹; Z_{ef} is the effective rooting depth (m), assumed to be 1 m in our analysis; K_s is the soil hydraulic conductivity (m s^{-1}), which is linked to the soil water potential by $K_s = K_{sat} (\Psi_{sat} / \Psi_s)^{3/b+2}$ (Campbell, 1974), where K_{sat} and Ψ_{sat} are respectively the conductivity and the water potential at field saturation.

Taking into account Eqs.(9) and (10), Eq.(6) can be rewritten as

$$r_s = \frac{r_{13} / (1 - \Psi_s / \Psi_{cc})}{1 - (r_{sp} I E_x) / (\Psi_s - \Psi_{cc})} \quad (12)$$

with $r_{13}=r_{smin}F_1(S)F_3(D)$. Eq.(12) is an expression similar and functionally equivalent to Eq.(5), when rewritten as $r_s=r_{sn}/(1-E/E_x)$. Matching term by term these two equations leads to

$$r_{sn} = r_{13} / (1 - \Psi_s / \Psi_{cc}) = r_{13} F_4(\Psi_s) \quad (13)$$

and

$$I E_x = (\Psi_s - \Psi_{cc}) / r_{sp} \quad (14)$$

Consequently, it appears that Monteith's parameterization of canopy stomatal resistance is not different from the Jarvis approach since the former can be inferred from the latter. The two parameters (r_{sn} and E_x) of Monteith's relationship can be interpreted in terms of the parameters and functions making up the Jarvis model and their physical significance appears now clearly. r_{sn} represents the canopy stomatal resistance when the leaf water potential is equal to the soil water potential ($Y=Y_s$), i.e., at zero transpiration (conditions experimentally encountered at pre-dawn). E_x represents the flux of water extracted from the soil when the leaf water potential is equal to the limit value Y_{cc} (i.e. its lowest possible value according to the parameterization used for F_4). It is the maximum flux of water the canopy can potentially extract from the soil.

The issue that arises now is the dependence of the canopy minimal stomatal resistance r_{sn} upon water vapour saturation deficit. To Monteith's mind, r_{sn} cannot depend upon saturation deficit, since in Eq.(3) the dependence of canopy resistance upon transpiration theoretically replaces the dependence upon saturation deficit. However, the matching of the two models leads to this apparent double dependence (r_{sn} is a function of r_{13} and then of $F_3(D)$, as shown by Eq.(13)). It is possible to keep only one dependence (that upon transpiration) by assuming with Lynn and Carlson (1990) that stomata do not respond directly to D (but indirectly through Y) and by putting then $F_3(D)=1$. From a pragmatic viewpoint this idea seems recommendable. In effect, this alternative leads to a sound and simple interpretation of the action of saturation deficit on stomatal aperture: When D increases, transpiration increases and consequently leaf water potential decreases according to Eq.(10) (assuming Y_s and r_{sp} to remain constant), which provokes a stronger stomatal closure.

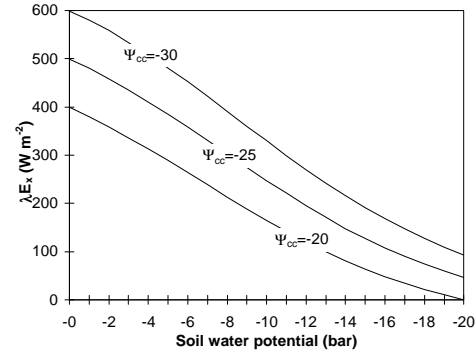


Fig.1- Maximum canopy evaporation $I E_x$ (given by Eq.(14)) versus soil water potential Y_s for different values of leaf water potential Y_{cc} corresponding to a complete stomatal closure (defined by Eq. (9)).

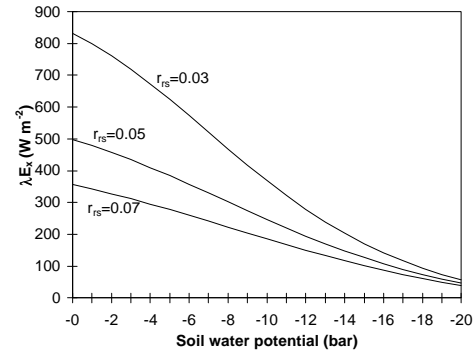


Fig.2- Maximum canopy evaporation $I E_x$ versus soil water potential Y_s for different values of the root-stem resistance r_{rs} .

NUMERICAL RESULTS

For a particular type of soil, characterised by fixed values of K_{sat} , Y_{sat} and b , and a given vegetation, characterised by fixed values of Y_{cc} , r_{rs} and Z_{ef} , the soil-plant resistance r_{sp} and then the maximum canopy transpiration $I E_x$ depend only upon the soil water potential Y_s . The values of the parameters used in the simulations are those given in the text. For the soil we took: $K_{sat}=6.3 \cdot 10^{-6} \text{ m s}^{-1}$, $Y_{sat}=-0.03 \text{ bar}$ and $b=7.1$, which correspond to a sandy clay loam. Fig.(1) shows the variation of $I E_x$ as a function of Y_s for different values of the limit leaf water potential Y_{cc} . $I E_x$ is an increasing function of Y_s : When Y_s passes from 0 to -20 bars, $I E_x$ is divided by 10, passing from 500 to 50 W m^{-2} (for $Y_{cc}=-25 \text{ bars}$); and for a given value of Y_s , $I E_x$ increases when the limit leaf water potential Y_{cc} decreases. $I E_x$ is also a function of root-stem resistance as illustrated in Fig.(2). Fig.(3) gives the variation of the minimum stomatal resistance r_{sn} as a function of solar radiation S for different values of soil water potential. In the expression of r_{sn} given by Eq.(13) it is assumed that $F_3(D)=1$, which means that $r_{13}=r_{1}=r_{smin}F_1(S)$. In this way,

the minimum canopy resistance r_{sn} depends only upon solar radiation through $F_1(S)$ and soil water potential Y_s . r_{sn} appears to be a decreasing function of both solar radiation and soil water potential.

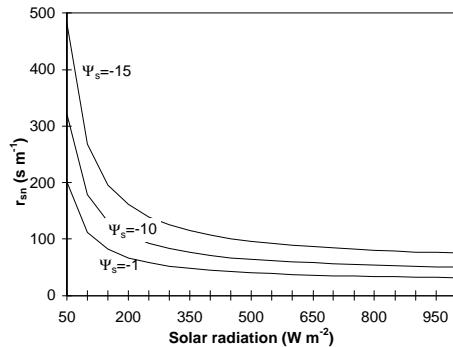


Fig.3 - Minimum canopy resistance r_{sn} (given by Eq.(13)) versus solar radiation S for different values of the soil water potential Y_s (bar).

CONCLUSION

The formulation of canopy resistance recently proposed by Monteith (1995b) has been examined and compared to the more common Jarvis type parameterizations. It appears that Monteith's formulation is not fundamentally new and can be inferred from Jarvis' one when the stress function $F_4(Y_l)$, involving leaf water potential, is expressed in the form of a hyperbolic function (Eq.9)). The perfect matching requires also that stomata do not respond directly to air humidity, but indirectly through transpiration and leaf water potential. This means that the stress function for air humidity $F_3(D)$ (in the Jarvis formulation) equals unity.

The two parameters of Monteith's formulation can be expressed in terms of the functions and parameters making up the Jarvis model. The minimum stomatal resistance r_{sn} represents the canopy stomatal resistance when the leaf water potential is equal to the soil water potential ($Y_l=Y_s$ and $E=0$), all other conditions being equal; and the maximum rate of transpiration E_x represents the flux of water extracted from the soil when the leaf water potential reaches its lowest possible value (according to the parameterization used for F_4): It is the maximum flux of water which can be extracted from the soil by the canopy.

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